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A Proposed Framework for Agile Reverse Engineering

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Abstract: Agile manufacturing enables an enterprise to introduce new products rapidly into the competitive markets. Reverse engineering offers tremendous advantages over product development. The paper proposes the combined agile reverse engineering approach for the companies seeking agile manufacturing. The paper will outline a practical framework and characterise the agile reverse engineering and its applications.

Key-Words: Agility, Reverse Engineering, Digitization, Coordinate Measuring Machine

1 Introduction

Agile manufacturing is a new business concept developed in 1990s, and it may be defined as an organisational ability to grow in a high level competitive environment through the quick response to rapidly changing markets [1]. Continuous and unanticipated changes are the principal driver to become agile, creating the need for massive reorganizations. To be able to introduce new products into markets as quickly as possible, the production system should be changed from traditional system to agile system.

Product design largely influences the production system. According to Groover [1] "decisions made in product design determine approximately 70% of manufacturing cost of a product". In this respect, equally important is the high quality and the short time-to-market. Therefore, to fulfil the requirements of agile manufacturing, agile product design is of utmost importance. In this way, Agile Reverse Engineering (ARE) can be principally seen as an approach which can offer tremendous advantages over product design in an agile enterprise. The paper will highlight the importance of agile reverse engineering, outline an ARE framework and discuss the relative challenging aspects for the companies seeking to be agile.

2 Overview of Reverse Engineering

Reverse Engineering (RE) is the process of accurately and quickly producing a model of an existing system or object. The object or system which is employed in a RE process can be either hardware or software (this paper merely focuses on RE of hardware). It is important to emphasize that RE should not be equated with copying an existing product; rather it is an advanced way to acquire a design concept in order to create a digital model and optimise the product. RE is normally associated with shape and features, however, in the broadest sense RE deals with study of design intents and mechanisms.

2.1 RE Applications

RE is not a new phenomenon and in recent years it has been increasingly applied in different fields of science from medicine to product inspection. An integrated RE system would give the organization several advantages, outlined below.

(I) Creating digital model for products which have no original model including old products and out-sourced products [2]. RE permits the company to have a fully digitized archive that is very helpful for rapid product development.

(II) RE enables the designers to start a design from an available physical model. It can be a great starting point for the complex parts. In most of aesthetic design, particularly in automobile industry, the designers prefer to make a real-scale clay model and create the 3D model or even produce a real 3D prototype by using the RE techniques. RE procedure can be used to create complete or partial model, e.g. portion of a body panel.

(III) In modifying a product, the relative functional Computer Aided Design (CAD) models might be unusable mainly due to shop floor changes and, therefore, the CAD model must be updated. So instead of using the old CAD data, RE can assist in acquiring information from existing parts or part elements, in order to refine the digital model. In brief, part-to-

CAD reverse engineering allows easier modification of the design.

(IV) Nowadays, there is a vital need in the high level competitive markets to redesign the products - either competitor's products or self produced products- mainly for needful evaluation or to perceive the market defect. Intellectual exploitation of the RE technologies has been noticed by companies for analysing and understanding the competitor's products, especially for the products competing in the same market. Moreover, a short lead-time in product development cycle has resolved itself into a crucial goal. By using reverse engineering technology, it is possible to attain this goal.

(V) In the inspection process of the complex shaped parts, the existing CAD model can be compared with the model created by RE [2].

2.2 Steps in RE

There are three major steps to accomplish a RE process: part digitization, feature extraction, and CAD modelling [3]. The working process of RE is depicted in Fig. 1. Digitization can be simply defined as acquiring point coordinates from part surfaces [3]. The quality of the final model depends largely upon the data acquisition perfection. The task of planning digitization algorithm is time-consuming and requires experience. Few numbers of iterations can considerably improve the accuracy of the final model. As a consequence digitization algorithms should be an iterative one. Digitization methods can be generally categorized into contacting and non-contacting methods.

Contacting methods are normally utilized where just a few points could define a surface. When a large number of points have to be touched, the measuring process will be excessively protracted. Coordinate Measuring Machine (CMM) is the most well-known contacting digitizer. CMM is the most advanced dimensional measuring instrument due to its great flexibility, high measurement speed and accuracy. In using CMM, there are a number of parameters to be considered, the major ones are measuring range, accuracy, measuring speed, probe system, software module, and supplementary accessories such as programmable fixtures and part-handling devices.

Sophisticated CMM probe management needs to be executed in RE to reduce the operation time. This involves making decision in terms of probe type, probe configuration, probe changing systems, stylus changing system, styli configurations, etc.

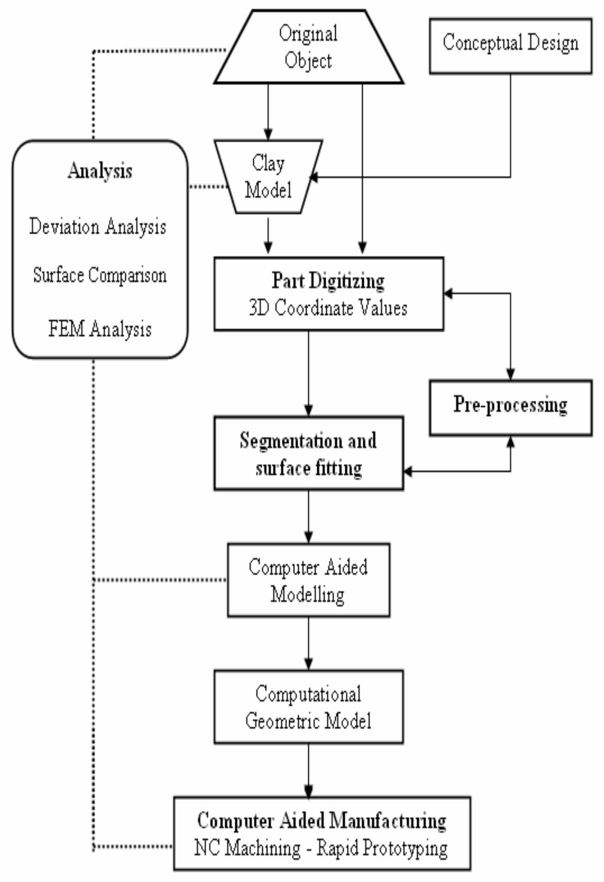

Fig. 1 Basic Phases in RE

There are two modes for performing tactile probing; (1) Discrete point probing using traditional touch trigger probes. (2) Scanning with analogue probe systems taking continuous measuring. These probes are particularly helpful when the number of points to be taken is considerably high. In comparison with touch trigger probes, scanning probes are more expensive. Other contacting digitizers include:

- Measuring robots (also called Articulated CMMs): Measuring robots are generally less accurate than CMMs but more cost effective. Also they can be equipped with both types of digitizers. They benefit from a compact structure which provides better flexibility and makes them suitable for hard-to-reach situations and special cases like parabola antenna [4].
- Numerically Controlled (NC) machines equipped with a measuring probe. In this case, the process is directly shifted to the manufacturing process. As a side benefit, the process is completed without a CMM and therefore results in a more profitable process and simpler data transfer [5].

Non-contact methods involve a wider range of techniques including optical, acoustic and magnetic methods. Using these methods data is collected quickly and densely. In optical methods, a high power light source typically illuminates the surface of interest and then a sensing device such as video camera intercepts the reflection of the surface. Subsequently, an appropriate technique should be used to determine the position of a surface point relative to a reference plane. Various light sources can be utilized in optical systems. Laser is the most common high energy light source. Laser-based scanners are fast and relatively accurate. Laser scanners are able to obtain large amounts of surface data in a short period. Often non-contact digitizers have lower cost compared to contact digitizers.

Following the digitization process, data points must be grouped into sets and then each set should be appropriately fitted to a single surface. These activities constitute segmentation and surface fitting as the most critical part of RE. In practice, however, the measured results could be incomplete and inaccurate. The data points set, accordingly, needs to be pre-processed to prevent the curves and surfaces from passing through the problem points. Afterwards, geometric model needs to be created using the extracted features through CAD systems. Within the CAD system a number of tasks such as compensations and model modification have to be done. Finally, identical copy of the object is fabricated through NC machining or rapid prototyping (RP).

3 Case Study

The authors proposed to critically investigate a CMM-based reverse engineering process from a practical point of view. The main concern is to carry out the process with minimal operation time. In doing so, measurement by single probe orientation and avoidance of multiple setups are in demand. Fig. 3 shows the used CMM which is located in the Brunel Centre for Manufacturing Metrology.

The chosen artefact is a helmet used especially for pedal cyclist. The helmet contains 11 vents to ensure a cool head. Because of the symmetrical shape of the helmet only one half needs to be measured. The circular vented hole located in the helmet's symmetry plane is the determinative factor to define the workpiece coordinate system. Without this circle hole, defining the helmet coordinate system is a very hard task. Accordingly, the circular hole should be fixed in XZ plane; so the helmet's symmetry plane will be parallel to XY plane as shown in Fig. 4. This made it possible to easily define the workpiece coordinate system.

Fig. 3 The Mitutoyo FN 503 CMM

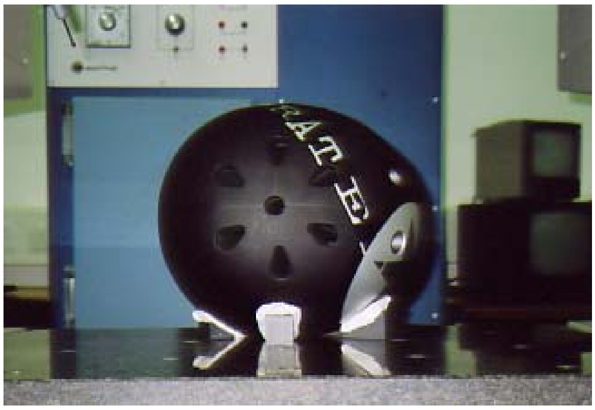

Fig.4 Positioning of the helmet (front view)

The employed probe system is Renishaw TP2 probe. The motorized probe head provides a variety of configurations. There is only one configuration used to measure all sides of the helmet, where A- angle and B-angle are 45˚ and 165˚ respectively.

In addition, it is important to determine the number and the position of the points to be taken. Basically, a large number of points are not necessarily useful for every part. To be able to create the CAD model, a set of curves should be measured. The set encompasses the helmet's symmetry plane and the curves parallel to this plane. Aside from the curves the contour should be measured separately. The lack of full looking over the part is the most significant restricting factor in measuring the contour. Also as the movement of the probe is being controlled in the close vicinity of the helmet, it is essential to ensure only the stylus tip touched the surface. CMM tends to make serious errors once the probe could not touch the surface in a normal direction. Improper probing direction has an adverse effect on the entire process, particularly on probe radius compensation.

Fig. 5 presents the helmet's CAD model provided by Alias Studio-tools 11. It is observed that the interrelation between digitization planning and CAD model planning should be properly considered.

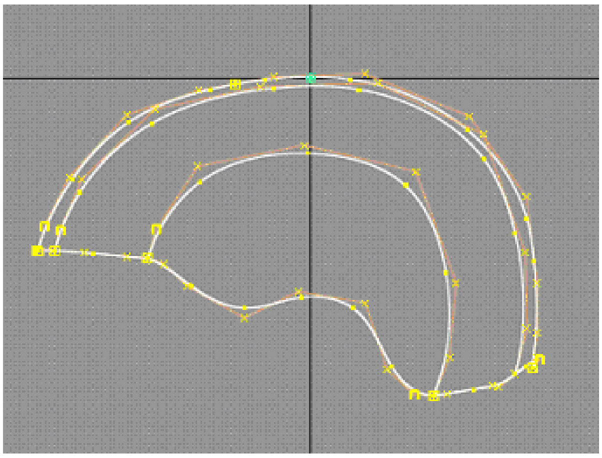

Fig.5 Wire-frame for half of the helmet – Top view

Moreover, it was observed from this study that the probe orientation and the limited measuring volume are the main restricting factors to perform automatic data collection. In effect, the measuring volume should be at least twice larger than the part volume, although a machine in a larger size tends to be less accurate. Also due to lack of the essential information about the test piece, it may be somewhat impractical to apply off-line programming.

Although the aim was to digitize the helmet quickly, taking the points from the part surface using the CMM took a whole day. Considering the various aspects of the problem, it seems horizontal-arm with rotary table or laser scanner could be a better solution to agile RE in this case. Nowadays, CMMs are attributed to traditional CARE (Computer-Aided Reverse Engineering) methods. However, despite the fact that using the CMM is normally tedious and time consuming, faster methods such as laser scanning are still devoid of high accuracy provided by the CMMs. Future works for CMMs will concentrate on long-term dimensional stability, faster drive system, and software evolution.

4 Characterizing an ARE system

An ideal ARE system is a fully automated system in which the decisions are made by the system itself. Such a system must be robust, precise, fast and cost effective. In fact, ARE is a powerful sub-system to fulfill the requirements of agile production system. ARE can serve the enterprise to

- Accomplish cost-effective product development with short lead-time
- Produce customizable products
- Produce upgradeable and reconfigurable products
- Increase the quality
- Launch innovative products

As a consequence, the enterprise will be able to thrive and gain the competitive advantages. However, agile RE requires high-skilled people, high-tech facilities, and excellent management structure. A number of key issues in an ARE system need to be addressed.

4.1 Appropriate Digitizer Selection

Justification of the suitable digitizer is based upon four parameters which have to be carefully considered at the starting point of the RE process. These parameters include [2]: part complexity, surface type, accuracy and speed. It should be pointed out that the demand for accuracy and other considerations such as financial affairs should converge in a balance point. Also the close relation between accuracy and speed force the user to choose the speed someway that the accuracy remains desirably.

4.2 Usage of Multi-sensor RE

The tendency to use multi-sensor CMM-based system with combination of different sensing elements would be particularly useful for ARE applications. Such a system can consolidate the strengths of the sensors. A well-known probe assembly is the combination of a touch probe and the optical video probe.

4.3 Feature-baser RE

Representing part geometry using manufacturing features is a new method whereby better description of part geometry may be provided. There has been a tendency to use manufacturing features as geometric primitives, instead of triangulated meshes or surfaces patches. The main advantages of this changeover are as follows [6]:

- Accuracy enhancement
- Easier CAD modelling and manufacturing
- Feature-based RE obviates the need for robust computations

4.4 Digitization Uncertainty

Measurement uncertainty refers to estimation of potential impacts of the factors which influence the measurement results. In an ARE system more attention should be given to digitization uncertainty. It is necessary to consider uncertainty when the digitization strategy is planned. Whereas the digitization process usually needs iterative measurement, the digitization uncertainty can be taken into account as a useful parameter for the next strategy planning. Often, the uncertainties due to temperature, operator and workpiece are not considered. In contacting methods, the measurement uncertainty in the probe system is the most important source of uncertainty [7]. It seems that the subject of digitization uncertainty will remain as a challenge and future research directions in RE will aim to predict and minimize the digitization uncertainty.

Furthermore, there are a variety of practical problems in digitization which greatly influence the time and cost of RE, including calibration, positioning and holding the workpiece, accessibility, obstacle avoidance and path planning, occlusion, noisy and incomplete data, surface finish [8], [9].

4.5 Ideal Organisation of the Sampled Data

In order to recreate the object, the data must be accurate and consistent enough. In fact, digitization should be regarded as a dense sampling of the part surface. It means digitization is something more than normal measurement of parametric features. An integrated ARE system should be able to consider tolerance values for each surface fitting.

4.6 Integrated Information Flow

The performance of the RE process needs appropriate information flow. It implies that the measured data points have to be transformed into a recognizable format for the programme of surface approximation. Afterwards, the approximation outputs should be sequentially integrated and become applicable to be used in CAD/CAM systems. IGES (Initial Graphics Exchange Specification) is the acceptable CAD format of the scanned data, which is compatible with almost all of the existing CAD/CAM systems [10]. For Rapid prototyping systems, STL (Stereolithography) is the standard form of data transmission. The simplicity of representing 3D CAD data is the major advantage of STL files. On the other hand, the major disadvantage refers to the larger size of a STL file in comparison with its corresponding CAD file. RP systems can also use IGES files.

4.7 Integrated Environment

An agile system should be able to find and use the required resources whenever they are available. In an agile system, management is responsible for providing the resources. In essence, a measuring device like a CMM and CAD/CAM systems organize the environment of RE. The CARE requires integrated environment in which the process can be done entirely computer-aided. In such an environment, paperless RE is performed. Internet-based computer-aided reverse engineering provides new approach to the paperless environment of RE [11]. In other words the data provided by sensing device is transmitted between the work stations regardless of the distance. Accordingly, the ARE process can be performed at different locations, so there is no need to gather all the equipments and the experts in one place.

In addition, the demand for high accuracy digitization requires careful consideration of environmental factors, especially for instruments close to shop floor. There are two important factors to be considered: temperature and vibration. In effect, the best way for error elimination in this case is the usage of temperature-controlled and isolated digitizing room.

4.7 Accuracy Analysis and Error Reduction

Any RE process contains an error chain. The error chain can be divided into two sections;

1) From digitization to solid modelling: in this case the errors can be measured by a comparison between the measured results and the dimensions on the solid model.
2) From the solid model to manufacturing: by comparing the original shape with the manufactured part the rest of the error chain can be quantified.

4.8 Full Automated Process

There is an ambitious goal to make the RE process fully automated. It is becoming apparent that software modules play an ever increasing role in order to fully automate the RE process.

Automatic data acquisition is the first barrier in the automation of RE, especially for parts with complicated geometry. At this stage, it is possible to digitize the surface with the minimum number of points to build the skeleton of the surface. Then by using the nominal surface the probe can be used to take automatic measurements, but this time with more data points (a form of CAD-directed measurement). In this way, vision systems can be utilized to help contacting machines like CMMs in for example detecting the position of the probe and the workpiece in 3D space as shown in Fig. 6.

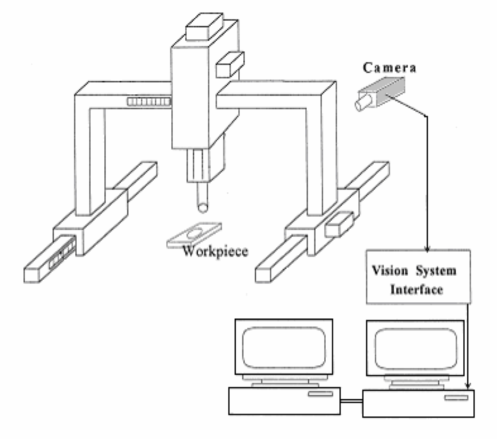

Fig.6 Outline of a developed CMM

Many researches are currently in progress to develop automated workpiece alignment system. The aim of the researches is to reduce the set-up time and increase the alignment accuracy by using 3D intelligent image processing system.

Automated feature extraction is the roadblock on the way to make the RE process fully automated. In fact, it is desirable to create the CAD model directly from the measurement data. The research orientation has shifted to automating the data segmentation, especially for optical methods. There is an approach to get rid of the feature extraction, obviously for those RE processes that do not need CAD model. With this approach, NC tool-path is directly generated from the measured data collection. [12].

4. Conclusions

Agility is a flexible strategy for ascertaining the company's main objectives such as profitability. Agile reverse engineering can be regarded as a holistic tactic to attain the strategic goals in an agile production system, with the proposed framework and steps in the context of computer integrated manufacturing. However, detailed implementation depends upon the requirements of each particular application. ARE system has to utilize the best available resources and developed technologies. Such a system should provide cost-effective product development with minimal operation time and long-term accuracy.

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